Systemic Security and the Role of Hierarchical Design in Cyber-Physical Systems

Sponsor: DASD(SE)

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Traditional Systems Engineering (SE) lacks external context inclusion in design selection M&S.

How can we ‘design-in’ Resilience at an earlier stages in the SE process?

*Cyber-Physical systems are a good model.*
Order and Form

**Dependent**
No dynamic couplings

**Interdependent & Independent**
Higher-order dynamic structures

**Independent**
Identical mutual information across parts

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Complexity

**Complicated**

**structure**

**Simple**

**HIERARCHY**

**HETERARCHY**

**ANARCHY**

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**Ordered**
Predictable

**Complex**
Somewhat predictable

**Chaotic**
Unpredictable

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Structure and function are intrinsically linked.
Structure and function are intrinsically linked.
Where Does This Leave Us?

Order and Form

*Defense systems of the future will tend toward ‘Ordered Complexity’.*

*Behavior not fully revealed via decomposition.*

Resilience

*Is contextual and emergent.*

*A System-only view is insufficient to understand and evaluate Resilience.*

Assurance

*Cannot be explicitly determined up front.*

*Is a measure of functional preservation by a control structure.*

Designing-in Resilience therefore requires both bringing in the context and elucidating structure-function relationships to behavior.
Where to Start?
– Think executable functional model of the ecosystem

- Extract system functional information
  - Directed Acyclic Graph

- Extract relationships between threat vectors and functional assets
  - Attack vectors captured in an attack tree
  - Semantic mapping of attack vector descriptors to targeted assets

- Extract a semantic mapping of Blue design patterns to:
  - Their functional capabilities
  - Assets they require to achieve capabilities
  - Critical functions/assets they will protect
  - Specific threat capabilities and/or threat assets they are designed to detect or counter through direct connective action
Reduce your space –
SME-guided analysis of system functions, attack vulnerabilities, and protection methods.

Protection methods serve as defense design patterns.

Create a “library” of security design patterns and associated threats.

• Prioritize threats and security implementations via decision tool.
• Perform trades on effectiveness, ease, and “cost” parameters.
• Narrow down threat and security implementation spaces.
State of Functional Capability or Asset $X_8 (t_i) = f \begin{cases} \text{node_self_class } (X_8), \\ \text{node_parent_class } (X_3, X_7), \\ \text{node_child_class } (X_9, X_{13}) \end{cases}$, $E_{X3_X8}(t_i, X_3(t_i)), E_{X7_X8}(t_i, X_7(t_i))$

State of Edge $X_8_{X13} (t_i) = g \begin{cases} \text{node_self_class } (X_8), \\ \text{node_coparent_class } (X_{12}), \\ \text{node_child_class } (X_{13}) \end{cases}$, State of Functional Capability or Asset $X_8 (t_i)$
Where to End?
– Test an executable functional ecosystem model

- Extract system functional information
- Extract relationships between threat vectors and functional assets
- Extract a semantic mapping of Blue design patterns

Create assurance test framework and patterns to:
  - Evaluate system response to threat
  - Maintain explicit knowledge of vulnerabilities and corrective patterns in design model
  - Build standard libraries of test strategies
How do we reveal complex structure-function relationships that may not be visible via the functional decomposition model produced in early-stage design?

Elucidate Structure-Function relationships by discovery.
Research Challenges

• What is different?
  — Deriving an ecosystem DiGraph
  — Dynamically executing DiGraph representation
  — Reveal hidden structure-function relationships via dynamic mapping

• What are the main challenges?
  — Scalability
  — Methodological rigor and consistency
  — Repeatable methodology to provide SEs with otherwise hidden insights that result in more effective design decisions
  — Extensibility of developed methods to a broad class of systems
Research Supports 2 Main premises

1. To evaluate security for a system with cyber elements, we must holistically evaluate
   • the system,
   • the threat(s), and
   • the protection (i.e., the security design pattern(s))
   as a single ecosystem.

2. Resilience is best understood as a non-functional property that emerges from
   the dynamics across interdependent elements in an ecosystem. A single
   system perspective or a strictly topological perspective will be insufficient.

Executable, contextual, and analyzable representation of
“Did our ‘designing-in’ for Resilience
indeed preserve mission-critical functionality in the face of the threat(s)?”